Simulation of AC, DC and AC-DC coupled hybrid mini-grids
In search of the most efficient system

Jorge Solórzano and Miguel Ángel Egido
Universidad Politécnica de Madrid-Instituto de Energía Solar
Avda. Complutense 30, 28040, Madrid, Spain
jorge.solorzano@ies-def.upm.es, +34-914533556

Renewable energy hybrid systems and mini-grids for electrification of rural areas are known to be reliable and more cost efficient than grid extension or only-diesel based systems. However, there is still some uncertainty in some areas, for example, which is the most efficient way of coupling hybrid systems: AC, DC or AC-DC? With the use of Matlab/Simulink a mini-grid that connects a school, a small hospital and an ecotourism hostel has been modelled. This same mini grid has been coupled in the different possible ways and the system's efficiency has been studied. In addition, while keeping the consumption constant, the generation sources and the consumption profile have been modified and the effect on the efficiency under each configuration has also been analysed. Finally different weather profiles have been introduced and, again, the effect on the efficiency of each system has been observed.

Keywords: mini-grids, AC coupling, partial coupling, efficiency

1. Introduction

Until recent years, off-grid renewable systems focused mainly on solar home systems (SHS), comprised of a few PV modules, 50-100W$_p$, a charge regulator, a battery and small loads, like some light-bulbs and a small TV. In recent years, since the early 2000s, the focus has evolved into larger and more efficient systems, called mini-grids, and usually combining different sources of energy, like PV, wind, hydro and diesel generators.

Since each energy source generates a different power signal, they must be adapted for a connection between them to be possible. This adaptation, and the connection, is known as *coupling* and it can be done in three different ways: DC, AC or a combination of both, AC/DC coupling or "partial AC-coupling".

Traditionally, and due to the DC nature of batteries and PV modules, SHS have always been coupled in DC. This avoids the use of power conditioning equipment and eliminates the efficiency losses introduced by these systems.

As the systems grew and different types of loads and different energy sources where introduced the trend shifted towards AC coupled systems. This provides great flexibility to the system designer and it is many times unavoidable due to a restriction of the DC components available and energy sources used. However, these configurations require more power conditioning equipment and, therefore, they have a lower efficiency, mainly due to the battery inverter.

Going one step beyond, it is possible to combine both topologies, DC and AC coupling, into what is called "partial AC-coupling". With this new topology all DC sources, like PV and batteries, and DC loads will be coupled to a DC bus and all AC sources, like wind or diesel generators, and AC loads into an AC bus. Doing this, we can avoid some losses from power conditioning equipment while maintaining the benefits of AC coupling.

2. Different system topologies

In this section the three different system topologies are presented.

2.1 DC coupled systems

Nowadays, DC coupled topologies are mostly used in small systems. Normally, in these systems only DC generators are used, mainly PV, although DC wind generators and DC diesel generators are also available. These generators are each connected to a charge regulator and through the regulator they are connected to a battery. DC consumers are also coupled to the DC side whereas AC consumers, if they exist, are connected to an inverter.

Although there are elements on the AC side, this system is considered DC coupled because all energy sources, PV and battery, are connected together in the DC side. The equipment in charge of coupling the PV generator and the battery is the charge regulator.

Presently, there are two types of charge regulators in the market, those with maximum power point tracking (MPPT) and a DC/DC buck converter (power conditioning) to lower the voltage from the PV generator to the battery voltage and those that simply connect the PV generator to the battery without any power conditioning. Although the second one has no efficiency loss due to power conditioning, the losses due to not coupling the PV system in its maximum power point (MPP) are usually larger than those due to the power conditioning [1, 2]. For this paper only charge regulators with MPPT will be considered.

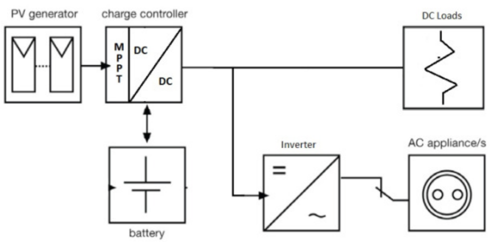

Figure 1: System layout of a DC coupled PV system

2.2 AC coupled systems

Generally, when systems increase in size they are implemented as AC coupled hybrid systems. In these systems DC coupling is completely avoided and the battery is equipped with extra power electronics. This provides great modularity, simplifying the addition of any new equipment, with the cost of having additional power conditioning equipment and, thus, additional power conversion losses.

In AC coupled hybrid systems an island grid is built. Normally, one of the components acts as a voltage source and constitutes the grid, setting voltage and frequency; the other AC generators feed in their power, acting as current sources. This results in a relatively simple control structure, however, it also has some drawbacks. Because the grid must always be kept alive, only generators that are always functioning can take on this task, eliminating PV or wind.

If the diesel generator is used for building the grid and is kept running during long periods only for this purpose, the overall efficiency of the system will be affected. In systems without a diesel generator, if the battery inverter is used it could occur that the whole system falls during low battery periods. When the sun comes out again the PV inverter will not work without the grid formed by the battery inverter and will not be able to charge the batteries.At this point the system is blocked and to unblock it the batteries would have to be charged independently of the system, with the obvious drawback and system down time.

In addition, if the PV generator is the main energy source and the loads are mainly used at night time, two unnecessary energy transformations are taking place: AC-DC to the battery and DC-AC. Considering a 92% weighted efficiency of the battery inverter [3], this results in a maximum efficiency loss of 15%.

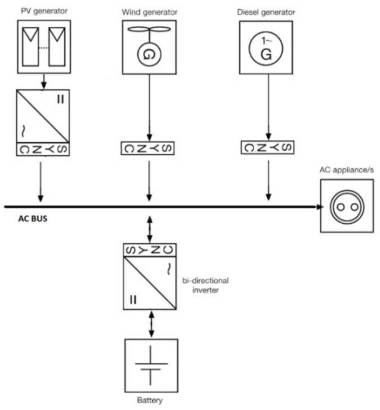

Figure 2: System layout of an AC coupled mini grid

2.3 Combined AC-DC coupled systems

From the combination of the two previous systems and extracting the advantages of each system a combined AC-DC coupled system is possible. Basically, this topology consists in coupling all DC sources and loads in DC and all AC sources and loads in AC.

Figure 3 shows a schematic of this topology.

In the combined AC-DC topology the bi-directional inverter is the brain of the system. It is in charge of building the AC grid and regulating the charge and discharge of the battery. It is a proven robust technology [4], it solves the problem of blocking the system as in AC coupling because the batteries can be charged without the grid, themodularity advantage remains, it is suitable for large systems and it gets rid of unnecessary efficiency losses in the battery inverter of AC coupled systems.

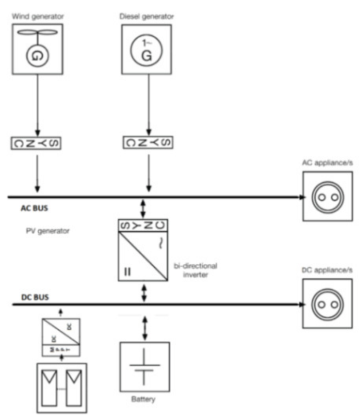

Figure 3: System layout of a combined AC-DC coupled hybrid mini-grid

3. Simulation of mini grids: in search of the most efficient system

With the points exposed in the previous section, it already seems reasonable that a combined AC-DC coupled hybrid mini-grid is the best solution for medium-large systems with at least PV and batteries. However, these systems are more complex to design, can turn out more expensive, due to more cabling and less available equipment, and could not always be the most efficient solution.

A short and very basic efficiency analysis was conducted in [4] which showed that AC coupling is more efficient when the energy is consumed directly when it is generated, mainly due to the lower efficiency of the battery inverter and charge controller in comparison with a normal PV inverter. In this section, with the aid of Matlab/Simulink, detailed simulations of the different topologies are conducted and the efficiency of each topologyis analysed in different situations.

It is important to note that only the efficiencies of the power conditioning equipment are considered, the reason being that these are the only ones that can be avoided by re-arranging our coupling topology. No matter which topology is used, the efficiency of the battery or of the diesel generator will not change. In addition, wind turbines and diesel generators in AC or DC can have different efficiencies. However, these are also not considered.

3.1 Description of the system

The mini grid that has been simulated is a project for electrifying a school, a small hospital and an ecotourism hostel. Table 1 shows the list of loads, their power and use, of the school. The school has 6 classrooms a kitchen and a computer room.

Lights Classrooms	6x140W	4 hours	3360Wh
Lights Computers	240W	3 hours	720Wh
Lights Kitchen	500W	1 hour	500Wh
TV	6x100W	1 hour	600Wh
DVD	6x100W	1 hour	600Wh
Computers	11x100W	3 hours	3300Wh
Printer	150W	1 hour	150Wh
Wifi	100W	3 hours	300Wh
Kitchen	1000W	1.5 hours	1500Wh

Table 1: List of loads in the school: their power and use.

Table 2 shows the list of loads, their power and use, of the hospital.

Lights	400W	14 hours	5600Wh
TV	100W	1 hour	100Wh
DVD	100W	1 hour	100Wh
Refrigerator	35W	24 hours	840Wh
Freezer	70W	24 hours	1680Wh
Computer	100W	2 hours	200Wh
Radio	300	1 hour	300Wh
Washing Machine	400W	3 hours	1200Wh

Table 2: List of loads in the hospital: their power and use.

Finally, Table 3 shows the list of loads, their power and use, of the ecotourism hostel. The hostel has a common area, a small computer room, a kitchen, a restaurant and 10 rooms. The rooms have lights and a plug for charging the computer or the mobile.

Lights	860W	4.5 hours	3870 Wh
Fans	400W	5 hours	2000 Wh
Printer	150W	1 hour	150Wh
Computers	12x100W	1.5 hours	1800 Wh
Wifi	70W	4 hours	280Wh
Kitchen	750W	6 hours	4500 Wh
Refrigerator	75	24 hours	1800 Wh
Washing Machine	400W	5 hours	2000 Wh
Mobile charger	10x10W	1 hour	100Wh

Table 3: List of loads in the ecotourism hostel: their power and use.

The total annual consumption of the loads is 27MWh. Figure 4 shows the combined load profile of the whole mini-grid. It shows that most consumption takes place at night, far from hours of renewable generation.

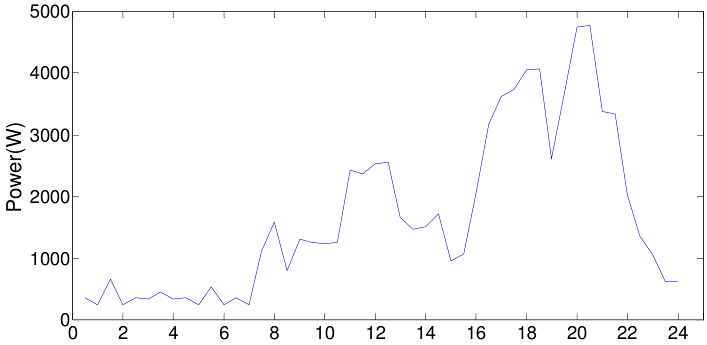

Figure 4: Load profile without DSM

This shift in time from renewable generation has many downsides. It forces the use of larger battery banks and it makes the system less efficient, due to battery charge and discharge cycles and the power conditioning equipment used. Shifting deferrable loads, like washing machines, to renewable generation periods is called demand side management (DSM) and it has been shown that is has a positive influence on renewable self-consumption of a system [5]. In this work the effect of DSM on the efficiency of a system is studied. Figure 5 shows the load profile of the whole mini-grid when DSM is applied, shifting the main consumption period to mid-day.

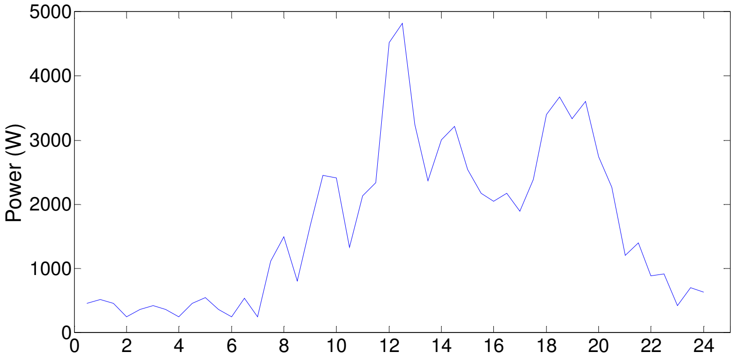

Figure 5: Load profile with DSM

3.2 Simulations

With the use of Matlab/Simulink various mini-grids have been designed to provide the necessary energy to the system and the losses due to the power conditioning equipment of the different configurations has been examined. Different combinations, by varying certain parameters, of the mini-grid have been simulated as follows:

- Energy generation: PV (10kW)-diesel-battery (150KWh) or PV(5kW)-wind(5kW)-diesel-battery (150kWh).
- Load consumption: Lights in AC side or lights in DC side. Possibility of using laptops and mobile chargers directly on DC
- Meteorological data: Radiation locations close to the equator (Puerto Rico 18ºN) and far from the equator (Madrid 40ºN).
- Demand side management (DSM).

An AC diesel generator is always used and it has been assumed to run on load-following mode; that is its energy is never used to charge the batteries. The wind generator is also always coupled on AC.

The accuracy of the performed simulations depends greatly on the accuracy of the efficiency curves used. When available the full efficiency curve has been used and when not the European efficiency has been used as a constant. Sometimes values from the manufacturer have been used and sometimes measured values have been used. Specifically, full curves have been used for the battery inverter (this one has been measured and is in accordance with the values from the manufacturer [6]) and the PV inverter and European efficiency values for the DC solar charger, obtained from the SMA webpage. Figure 6 shows the efficiency curves used.

From the efficiency curves it is observed that the SB5000TL is more efficient. However, it is also important to note that the battery inverter achieves its maximum efficiency at very low power, 10% of its nominal power, and it lowers off at higher power. This is important for battery inverters because they will usually work far from their nominal power, opposite of PV inverters.

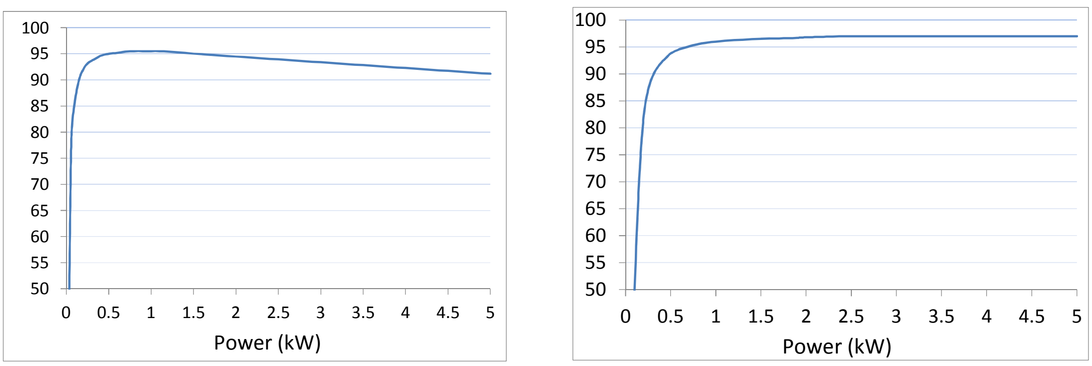

Figure 6: Efficiency curves of a) Sunny back up battery inverter and b) Sunny Boy 5000TL.

The result obtained for all the simulated mini grids is the percentage of energy lost in the power conditioning equipment with respect to the consumed energy, throughout a whole year. The calculation responds to equation [1].

$$E_{lost} = \frac{\sum Losses\ in\ power\ conditioning}{\sum load\ consumption} \quad [1]$$

3.3 Results

Table 4 shows the energy lost in the different simulated configurations:

System	Coupling	Lights	Location	DSM	*Diesel Energy (MWh)*	E_{lost}
PV-diesel	AC	AC	Madrid	No	6.79	12.1%
PV-diesel	AC	AC	Madrid	Yes	5.65	10.6%
PV-diesel	AC	AC	Puerto Rico	No	2.68	13.4%
PV-diesel	AC	AC	Puerto Rico	Yes	1.64	11.1%
PV-wind-diesel	AC	AC	Madrid	No	6.77	7.8%
PV-wind-diesel	AC	AC	Madrid	Yes	5.77	6.2%
PV-diesel	DC	AC	Madrid	No	5.62	6.46%
PV-diesel	DC	AC	Madrid	Yes	4.78	6.23%
PV-wind-diesel	DC	AC	Madrid	No	9.16	4.42%
PV-wind-diesel	DC	AC	Madrid	Yes	8.6	4.14%
PV-diesel	DC	DC	Madrid	No	2.68	5.4%
PV-diesel	DC	DC	Madrid	Yes	1.73	5.18%
PV-wind-diesel	DC	DC	Madrid	No	4.75	4.03%
PV-wind-diesel	DC	DC	Madrid	Yes	3.45	3.92
PV-diesel	DC	DC	Puerto Rico	No	0.85	6.12%
PV-diesel	DC	DC	Puerto Rico	Yes	0.48	5.65%

Table 4: Energy lost in power conditioning equipment with the different configurations

The annual generation of the different renewable sources is shown in Table 5 for the different systems.

	PV	**Wind**
PV-diesel	29.4MWh	-
PV-wind-diesel	14.7MWh	11.6MWh
PV-diesel_puerto Rico	40.4MWh	-

Table 5: Generation and consumption in the different type of systems.

In addition, the efficiency of the power conditioning equipment of loads which are normally fed in AC but work in DC were measured (Table 6): laptop computers and mobile phone chargers (of all the loads in the system, this type of loads represent 16.1%).

					Average
Laptop charger efficiency	44.1%	48.9%	75%	41%	**52.3%**
Mobile charger efficiency			27%	35%	**31%**

Table 6: Measured efficiencies of laptop chargers (top and mobile-phone chargers (bottom)

With these efficiencies, and supposing that we have the equipment available to do a DC/DC conversion from the battery voltage to the voltage of the equipment (5V for mobiles and typically 12-20V for laptops), other mini-grids are also simulated. The efficiency of the DC/DC converter is estimated at 95%.

For the simulation of mini grids with laptops and mobile phones feeding directly from DC the following results are obtained. In this case the losses are higher because the efficiency of the power conditioning equipment of consumer electronics is considered, and it was not considered in Table 4. When they are coupled in DC the losses are considerably reduced and the total annual consumption is also lower, now being 24.8MWh; so 2.2MWh are lost in power conversion of consumer electronics.

System	Coupling	Lights	Location	DSM	*Diesel Energy*	E_{lost}
PV-diesel	AC	AC	Madrid	No	6.79MWh	**20.2%**
PV-diesel	DC	DC	Madrid	No	1.31MWh	**5.1%**

Table 7: Energy lost in power conditioning equipment when considering losses in DC equipment, i.e. laptops, printers, router, mobile chargers.

4. Conclusions

From the obtained results it is clear straight away that partial coupling is beneficial in all situations. The efficiency of a system will benefit straight away from just coupling the batteries on the DC side, which can be easily done. It will also avoid the possibility of having the system blocked when the batteries are low and their inverter is in charge of building the AC grid.

For extra efficiency improvements, coupling the lights on the DC side and applying some DSM will also work almost always. It is also clear that some systems benefit more than other from partial AC coupling and systems designers should have this in mind because it might not be worth it for some systems: i.e. those with mainly wind generators producing in AC.

In PV-diesel systems what can really improve the systems efficiency is feeding equipment that allows it on DC, i.e. laptop computers. Most laptops work at voltages from 12-19V and converting from the battery voltage could be done at very high efficiency, over 95% instead of the 50% of the standard laptop charger. This is definitely an opportunity for product developers and mini-grid designers.

Further economic analysis must be carried out to fully validate the improvements of partial coupling.

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